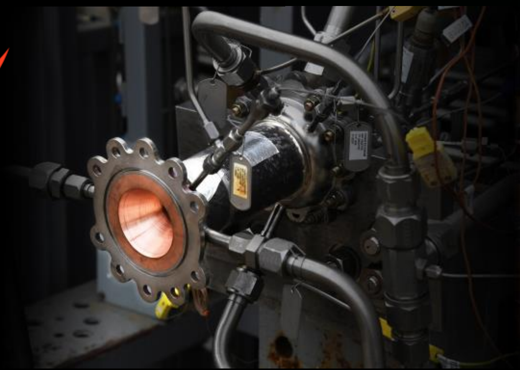

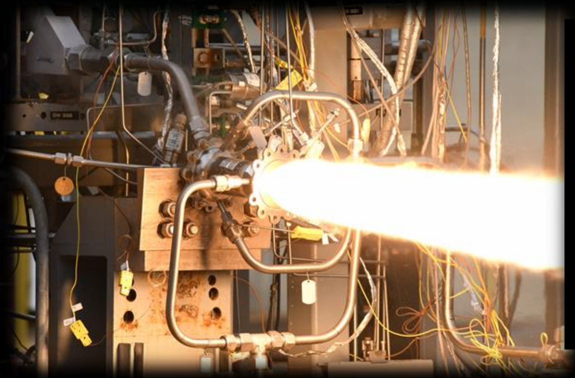

Additive Manufacturing and Hot-fire Testing of Bimetallic GRCop-84 and C-18150 Channel-Cooled Combustion Chambers using Powder Bed Fusion and Inconel 625 Hybrid Directed Energy Deposition

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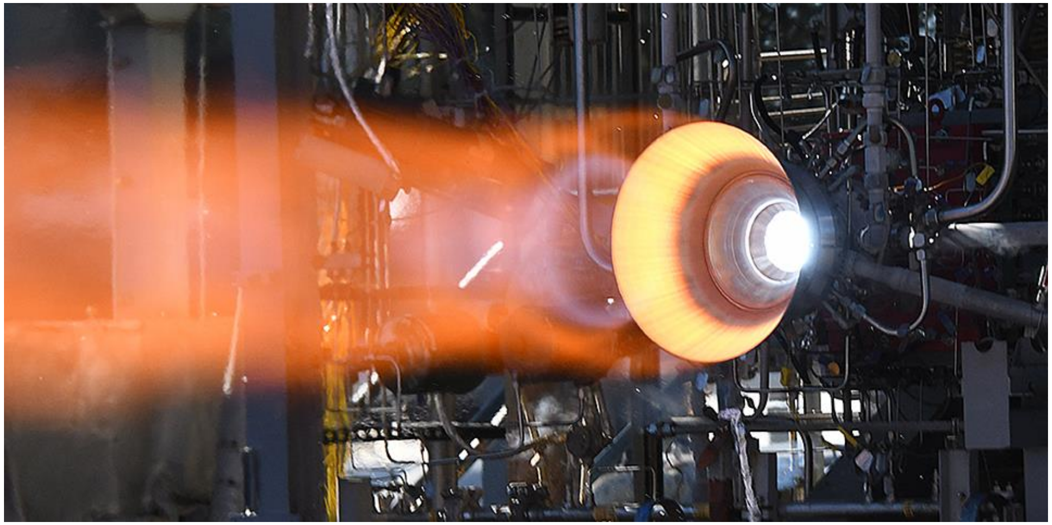
Background of ACO Program

- Starting in 2017, NASA and Virgin Orbit partnered under the NASA Space Technology Mission Directorate (STMD) Announcement for Collaborative (ACO) Opportunity providing a public-private development partnership for additively manufactured combustion chambers
  - Provides 50/50 cost share under Space Act Agreement (SAA) for development
- Focus was to evaluate bimetallic combustion chambers using additive manufacturing technologies leveraging unique capabilities at NASA Marshall Space Flight Center (MSFC) and Virgin Orbit
- Targets potential upgrades to Virgin Orbit's Newton 3 and Newton 4 combustion chambers that currently use mature traditional manufacturing technologies
  - Newton 3 is the boost engine and Newton 4 is the upper stage engine on the LauncherOne air-launch rocket
- Partnership program has successfully met all development objectives and completed new manufacturing technologies and capabilities for bimetallic additive manufacturing

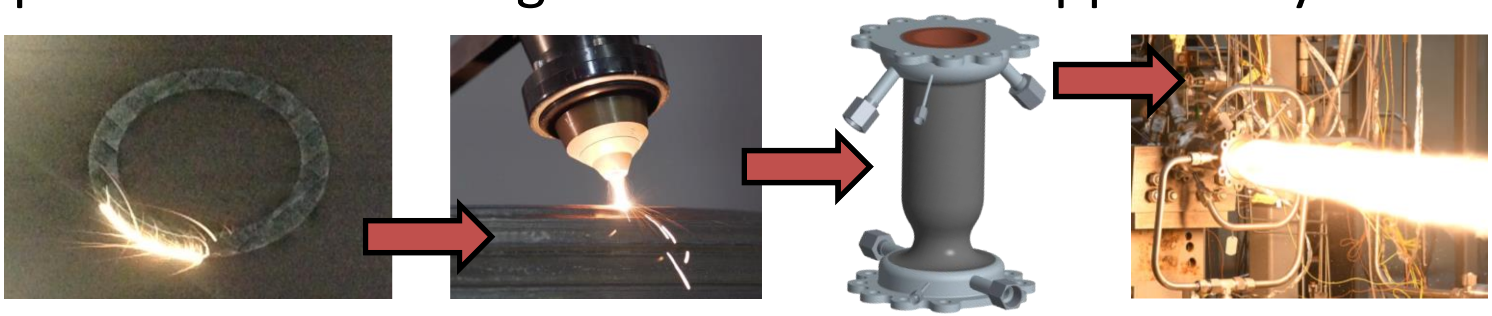
History of NASA Development

- NASA previously developed GRCop-84 (Cu-Cr-Nb) using the Laser Powder Bed Fusion (L-PBF), or Selective Laser Melting (SLM), technology for forming integrally-cooled combustion chambers
- A secondary bimetallic jacket was applied using Electron Beam Freeform Fabrication (EBF^3)
- Successfully completed hot-fire testing although observed distortion and shrinkage of the liner (35K-lb$_f$ thrust class)
  - Low Cost Upper Stage Propulsion (LCUSP) program



Development Goals of the NASA-Virgin Orbit ACO Partnership

- Investigate and provide comparison data for various copper-alloy liners using additive manufacturing
  - Advance SLM GRCop-84 process and develop a supply chain, building upon LCUSP program
  - Develop and advance the GRCop-42 material using SLM additive manufacturing; an alternate for GRCop-84 with higher conductivity
  - Evaluate C-18150 using SLM based on historical experience with wrought
- Develop process using directed energy deposition (DED) cladding process to apply a jacket and integrate manifolds
- Demonstrate fully integrated bimetallic chambers and reduction to fabrication cycle
- Complete hot-fire testing with the various copper-alloy liners



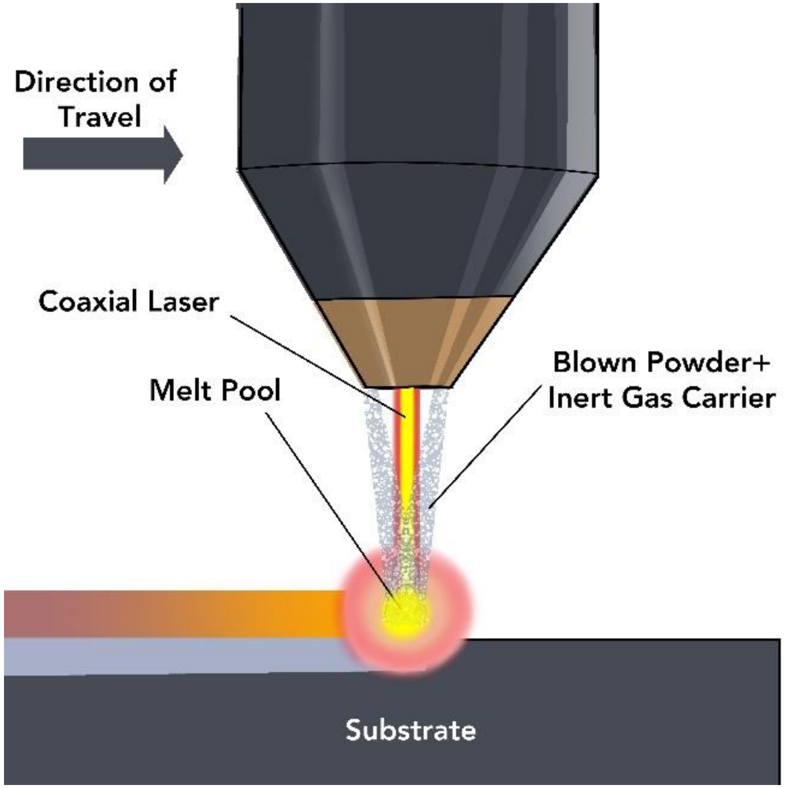
SLM/L-PBF **DED/Hybrid machining** **Hot-fire Testing**

Selective Laser Melting (SLM or L-PBF)

Uses a layer-by-layer powder-bed approach in which the desired component features are sintered using a laser and subsequently solidified.

Blown Powder Directed Energy Deposition (DED)

Freeform fabrication process using coaxial laser and powder blown into the melt pool to create features



Hybrid DED Technology

- Virgin Orbit has adopted and provided a unique capability with Hybrid DED Additive/Subtract machining center to integrally apply the jacket and provide interim machining
- Allows for a single setup of DED cladding/freeform fabrication and machining
- Allows for new opportunities with gradient and transition materials

Photo courtesy Virgin Orbit and DMG Mori Seiki

Copper-alloy Liner Material Selection

- Part of the development objectives was to evaluate various copper-alloys for use during chamber design and development
- Three primary alloys selected for evaluation:

  1. **GRCop-84 (Cu-8Cr-4Nb)**
  2. **C-18150 (Cu-Cr-Zr)**
  3. **GRCop-42 (Cu-4Cr-2Nb)**

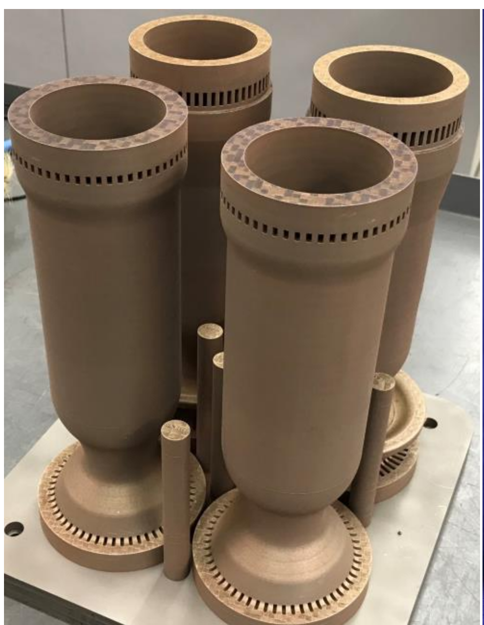
Element	GRCop-84	C-18150	GRCop-42
Cr	6.2 – 6.8	0.5 – 1.5	3.1 – 3.4
Nb	5.4 – 6.0	-	2.7 – 3.0
Cu	Balance	Balance	Balance
Zr	-	0.05 – 0.2	-

- Materials selected based on supply chain availability, maturity, cost, compatibility with additive manufacturing
- Selected **Inconel 625** as primary jacket material based on process maturity and compatibility with copper-alloys

Materials Evaluation and Hardware Development

Completed initial development work, characterization, and heat treatment to evaluate basic mechanical properties

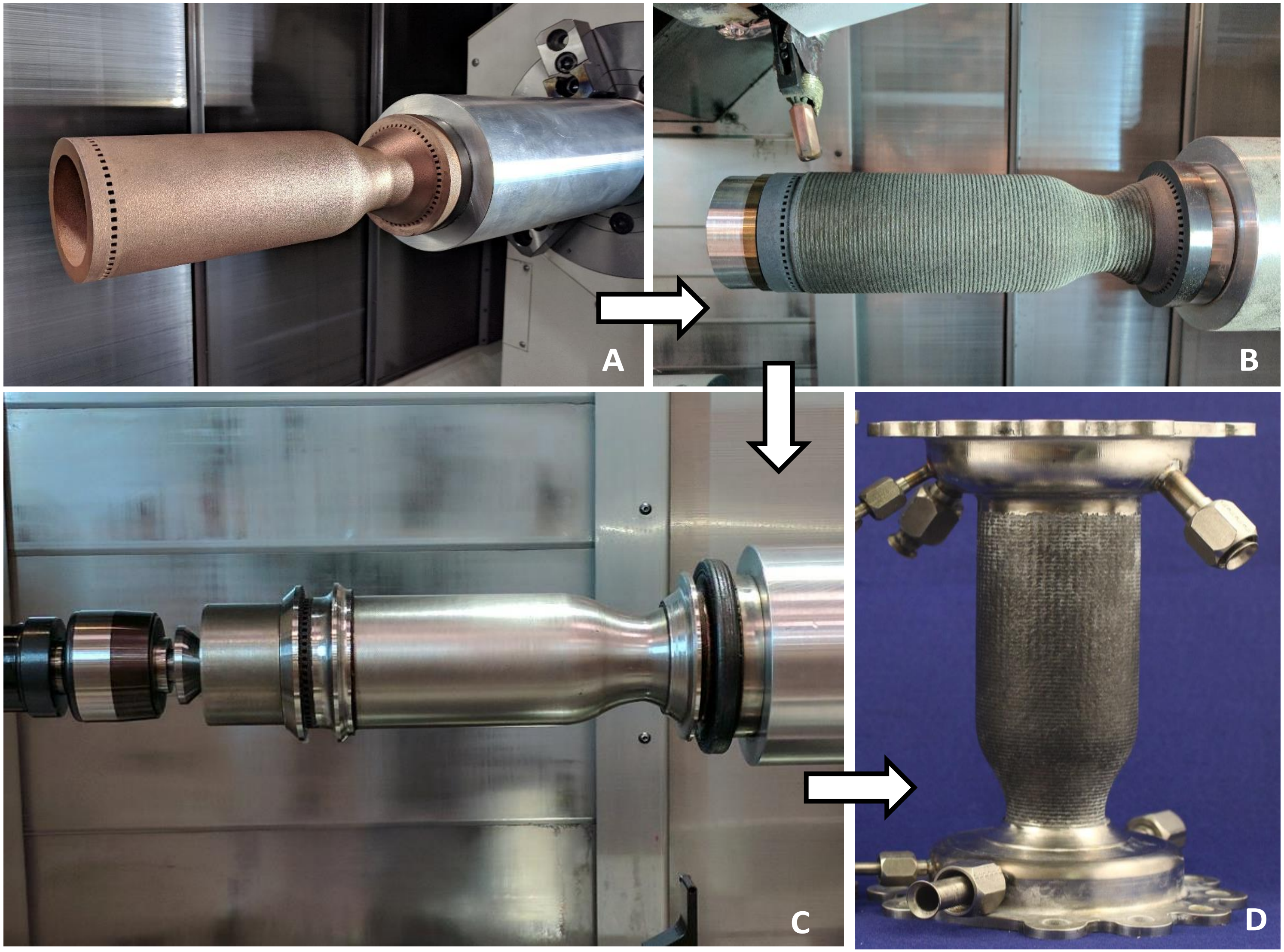
Material	Tensile	Yield	Elongation
	(ksi)	(ksi)	(%)
GRCop-84 – SLM, MSFC Concept M2	56.6	30.2	30
GRCop-84 – SLM, vendor	64.6	34.2	26
GRCop-42 – SLM, MSFC Concept M2	52	25.1	32.2
C-18150 – SLM, vendor	40	26	27



Chamber Test Units

Virgin Orbit #1 (VO1)	Virgin Orbit #3 (VO3)
GRCop-84	C-18150
HIP	HIP, Solution, Age
Inconel 625	Inconel 625

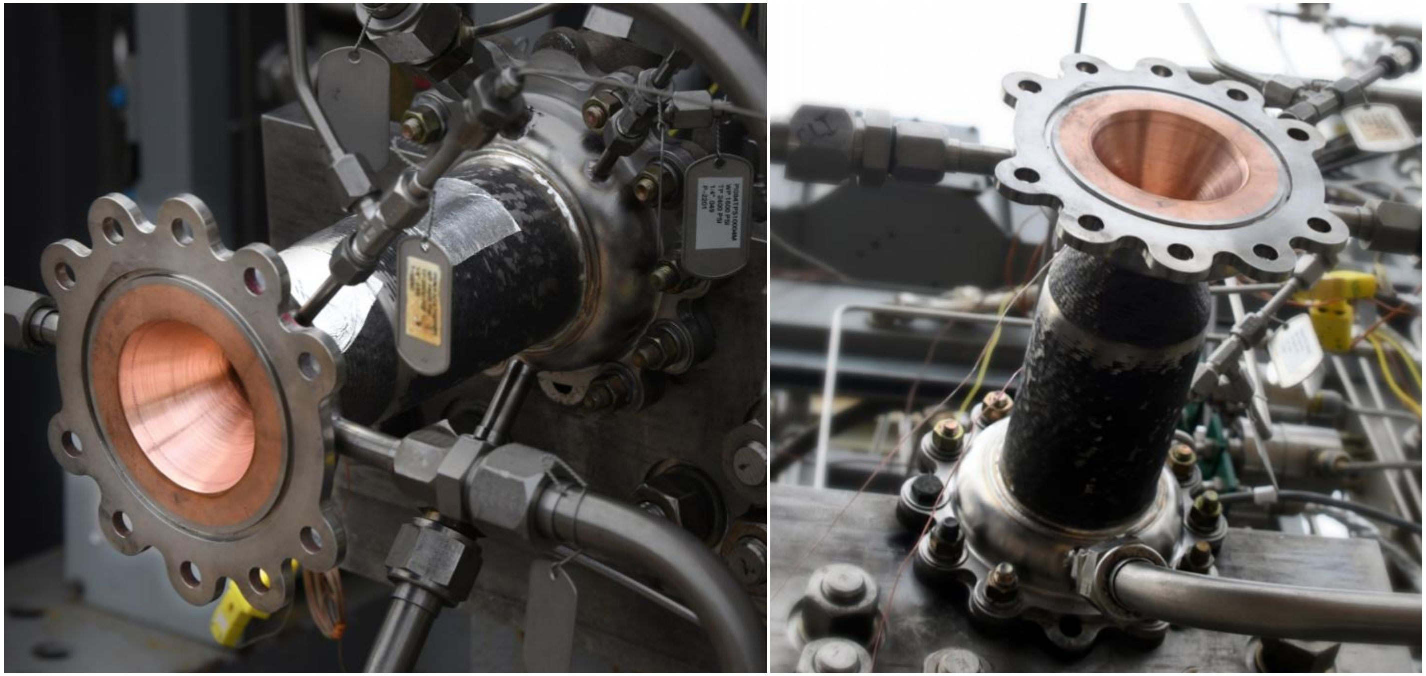
Fabrication Process Overview



A) Establishing datums in the DMG LT4300, B) Initial DED passes of the liner, B) C) Final machining of the liner, and D) Final configuration of the chamber.

Testing Overview

- Testing completed at MSFC Test Stand 115 (starting December 2018)
- Liquid Oxygen/Kerosene (LOX/RP-1)
- Triplet impinging injector (Additively Manufactured Inconel 625)
- Chamber Pressures (Pc) from 500-1,000 psig
- Mixture Ratio (MR) from 2.2 – 2.8

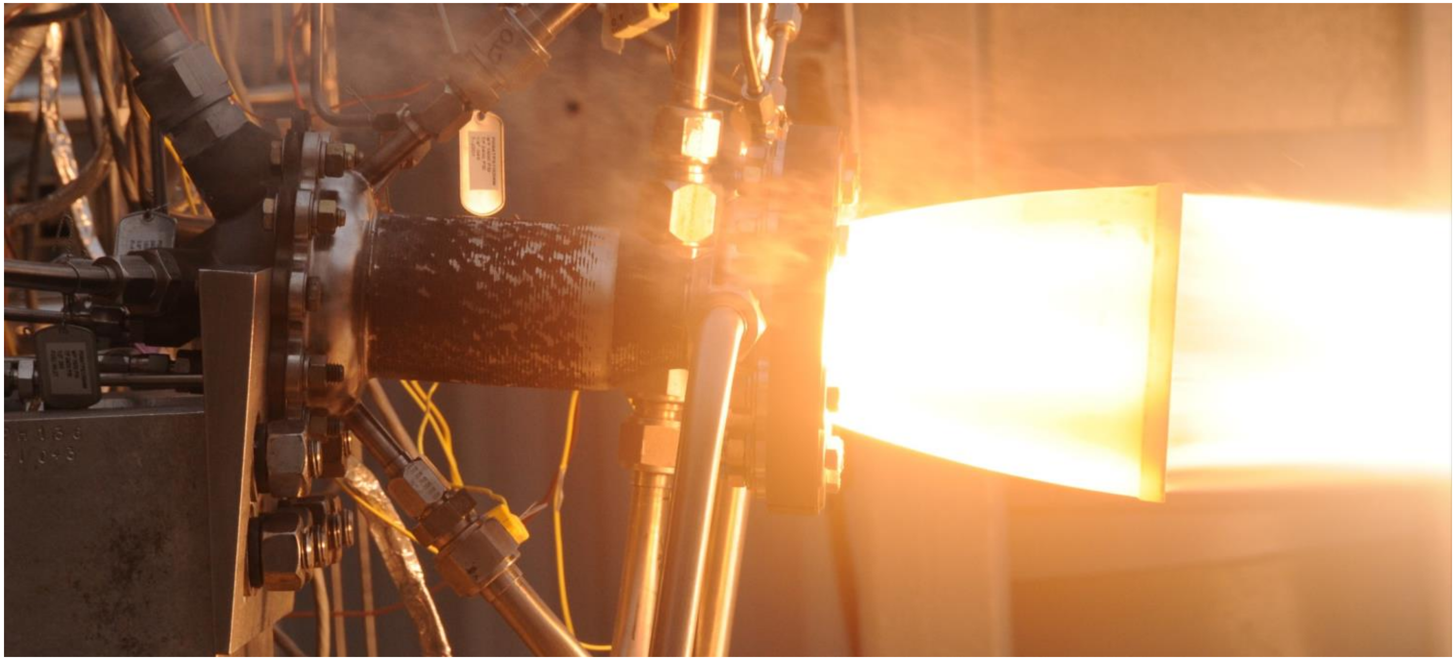


Bimetallic chamber installed at MSFC TS115

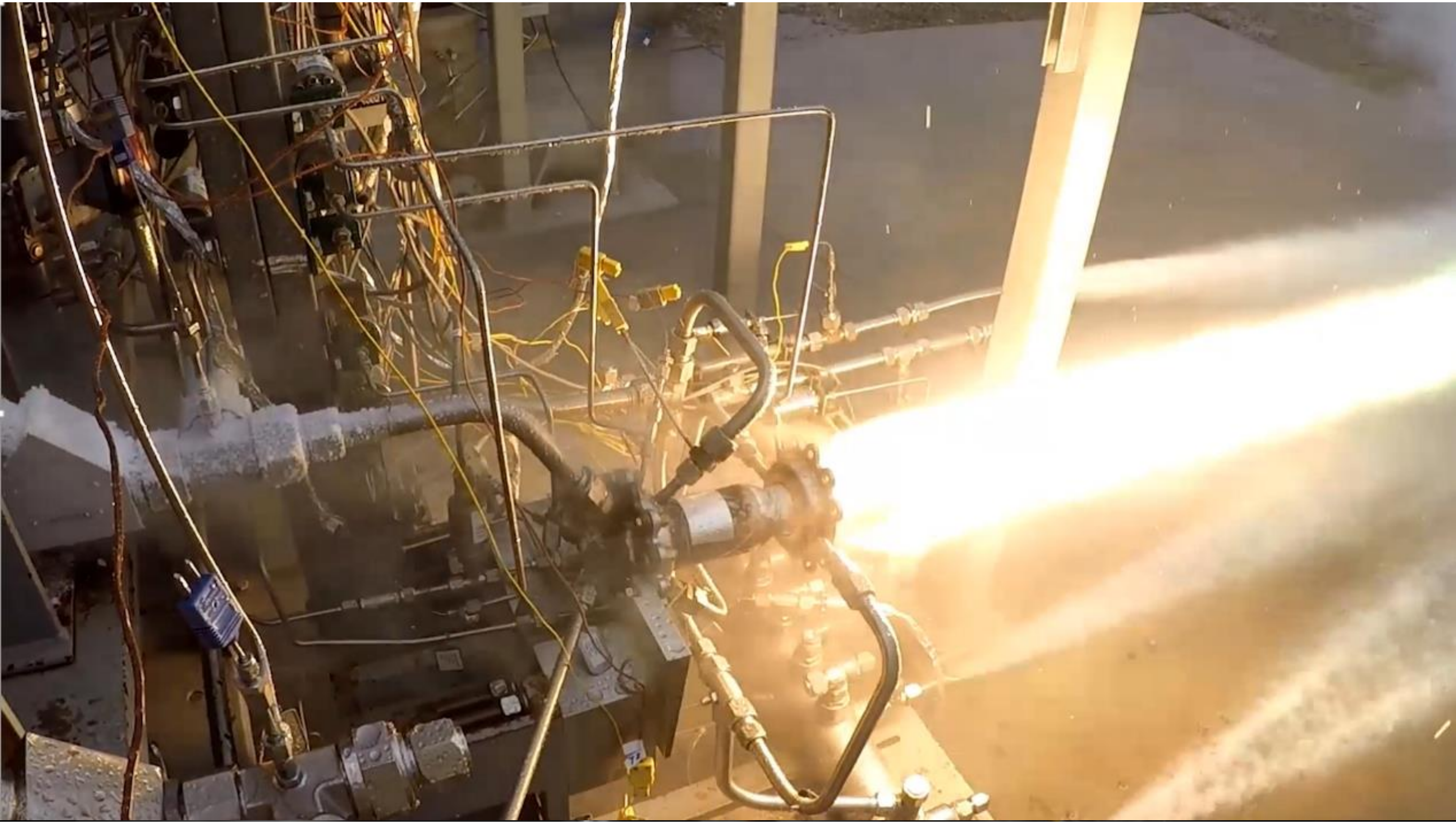
Summary of Results

- Completed 20 tests on (2) units; test durations to 60 sec
- Secondary objectives to evaluate the injector and characterize high temperature Carbon-Carbon (C-C) nozzle extensions (below)

	Peak Chamber Pressure (psig)	Peak MR	Starts	Accumulated Time (sec)
VO Chamber 1 (VO1)	1,048	2.84	11	475
VO Chamber 3 (VO3)	1,080	2.84	9	405

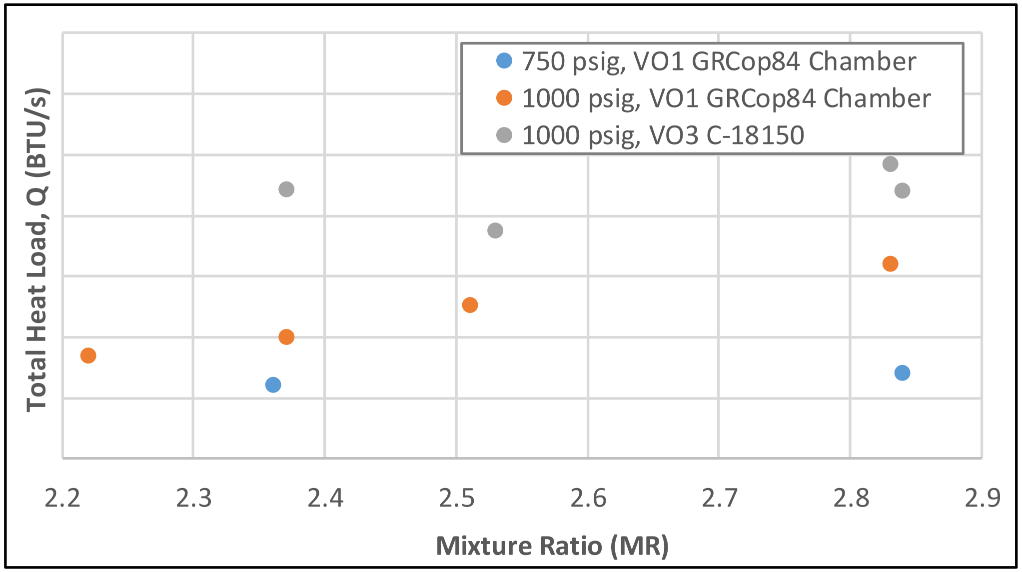


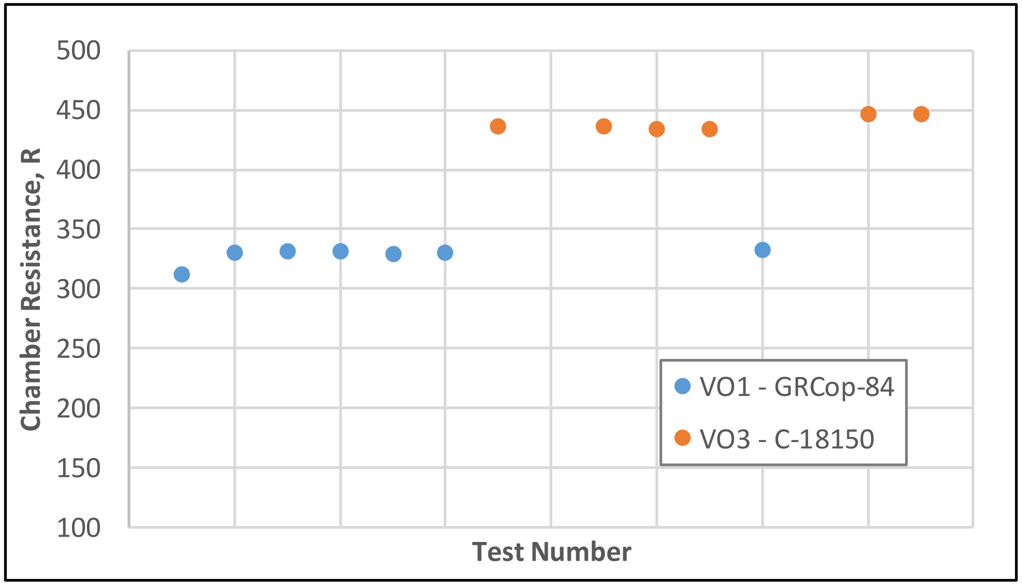
Hot-Fire Testing



Summary of Results

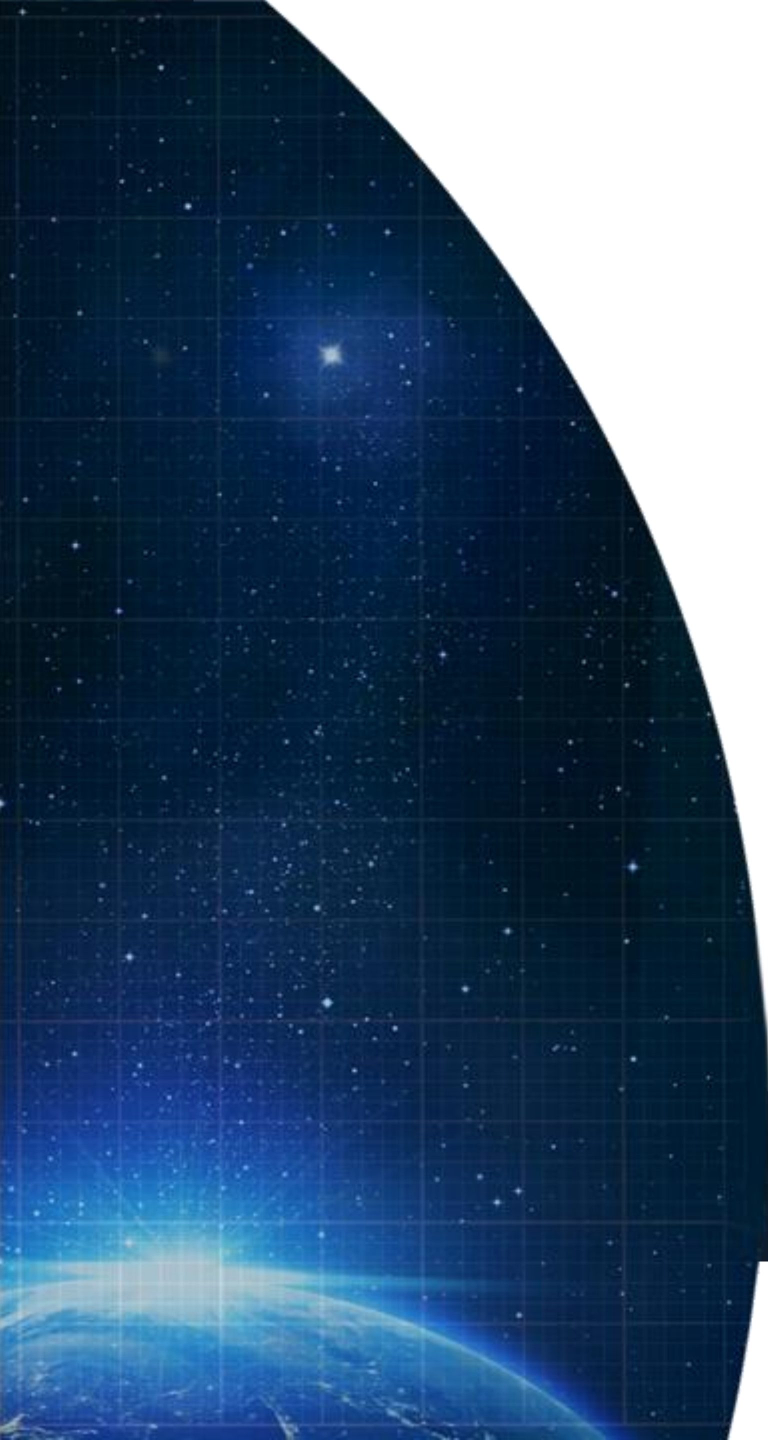
- All units performed well and no major issues observed
- Completed full evaluation of hardware and inspections after each test
- Observed differences in total heat load between the C-18150 and GRCop-84 chambers
- 30% increase in chamber resistant of C-18150 chamber based on higher surface roughness during SLM process





Program Summary

- Public-private partnerships between government and commercial space demonstrated successful co-developed processes and testing
- Demonstrated successful joints using the hybrid additive manufacturing technologies
  - SLM copper-alloy liners
  - DED structural jacket
- Completed fabrication of bimetallic hardware and completed testing of GRCop-84/Inco 625 and C-18150/Inco 625 hardware
  - Accumulated 20 hot-fire tests and 880 seconds on hardware
- Successfully demonstrated GRCop-42 SLM printing process and hot-fire tested under another program
- Lessons learned in fabrication process and being applied to trade studies to incorporate into block upgrades
- Non-proprietary data publically available



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